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Selectivity of gill nets for *Solea solea* (Osteichthyes: Soleidae) in the Adriatic Sea

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SUMMARY: Sole juveniles concentrate along the western Adriatic coast where they are targeted from spring to autumn by small-scale gill netters. As in spring–early summer 20 to 30% of catch biomass consists of individuals smaller than MLS (TL = 20 cm), the selectivity of sole gill nets was investigated in 2004-2005 in order to obtain useful information for developing management measures aimed at reducing the retention of undersized specimens and assuring the sustainability of this fishery. Twenty-eight fishing trips were performed using sole gill nets with 5 mesh openings (64.2, 65.2, 67.8, 70.2 and 71.8 mm) simultaneously. The gill net selectivity was estimated indirectly by applying the SELECT method and between-set analysis. The log-normal curve was found to fit single set data better than other models. The catch yields did not significantly decrease with the increment of mesh size: the biomass of undersized individuals in catches noticeably decreased from 16% down to 9% in the largest mesh size, whilst the sole that were longer than the MLS increased proportionally. In view of the lower economic value of smaller specimens with respect to the larger ones, adopting the 71.8 mm mesh represents a good compromise between the need to protect juveniles and the economic profit of gill netters.

Keywords: *Solea solea*, gill nets, mesh selectivity, fishery management, fishery resources, Adriatic Sea.

RESUMEN: SELECTIVIDAD DE LAS REDES DE ENMALLE PARA *SOLEA SOLEA* (OSTEICHTHYES: SOLEIDAE) EN EL MAR ADRIÁTICO. – Los juveniles de lenguado se concentran a lo largo de la costa oeste adriática donde son capturados desde la primavera hasta el verano con redes de enmalle de tamaño pequeño. En primavera y principios del verano el 20-30% de la biomasa capturada corresponde a individuos menores a la talla mínima legal (longitud total de 20 cm). Este trabajo ha estudiado la selectividad de las redes de enmalle para el lenguado durante 2004-2005 con el objetivo de obtener suficiente información para desarrollar medidas de gestión que reduzcan la retención de individuos demasiado pequeños y asegurar así la sostenibilidad de la pesquería. Durante este estudio se realizaron un total de veintiocho muestreos pesqueros usando simultáneamente redes de enmalle con cinco luces de malla distintas (64.2, 65.2, 67.8, 70.2 y 71.8 mm). La selectividad de la red de enmalle fue estimada indirectamente aplicando el método SELECT. El modelo que se ajustó mejor a los datos fue una curva de tipo log-normal. La captura no descendió significativamente con el incremento de la luz de malla. La biomasa de los individuos pequeños en las capturas bajó notablemente de 16% a 9% con el uso de la red de mayor luz de malla, mientras que los lenguados con mayor tamaño aumentaron proporcionalmente. Como los individuos menores tienen también un valor económico menor, el uso de la red de 71.8 mm de luz de malla es un buen compromiso entre la protección de los juveniles y la obtención de beneficios económicos para los pescadores que usan las redes de enmalle.

Palabras clave: *Solea solea*, redes de enmalle, selectividad de las redes de pesca, gestión pesquera, recursos pesqueros, mar Adriático.

INTRODUCTION

In Italy the mean annual landing of sole *Solea solea* (Linnaeus, 1758) amounts to about 3000 tons, 60% of which comes from the northern and central Adriatic Sea (ISTAT, 2002-2005). Although in this area the sole catches are less abundant with respect to those of other demersal fish, such as the European hake *Merluccius merluccius* and the red mullet *Mullus barbatus* (ISTAT, 2002-2005), this species plays an important role for fisheries due to its higher economic value per unit weight, which is around two and three times the price of hake and red mullet respectively. In the Adriatic Sea soles are caught all year round by rapido trawlers. In addition, sole juveniles that concentrate in inshore marine waters are targeted from spring to autumn by small-scale vessels (4-12 m Loa) using loosely hung gill nets with low buoyancy floats that allow the gear to partially lay down on the seabed; thus, favouring the capture of benthic fish (Grati *et al.*, 2002). The mesh sizes commonly used by gill netters are 64 and 68 mm (stretched), but some of them shift towards a 72 mm opening in autumn, in accordance with the growth of the species. Fishermen make daily trips to the fishing grounds located 2 to 6 km from the shoreline and exploit sole belonging to age classes 1 and 2 (Grati *et al.*, 2002). In spring and summer, when this fishing activity is greater, 20 to 30% of catch biomass consists of individuals smaller than the Minimum Landing Size (MLS = 20 cm TL; Grati *et al.*, 2002). These undersized specimens are not discarded but usually sold to retail.

However, the sole stock in the northern and central Adriatic Sea has been assessed only recently (2005-2006) and the available data indicate that the stock is fully exploited (GFCM, 2006), which has lead to studies aimed at reducing the capture of juveniles.

In the light of the state of the resource and given the relevance of static gears, understanding the impact of different gears which compete for exploiting this species is crucial for developing adequate management and conservation measures.

Based on these statements and taking into account the scarcity of information on the selectivity of the sole gill net fishery in the Mediterranean Sea (Francesconi *et al.*, 2005), estimates of gill net selectivity are necessary in order to adopt adequate management measures for maintaining the sole stock and assuring the sustainability of this fishery.

In order to fill in, at least in part, the existing gaps, the present study estimates the selectivity of sole gill nets indirectly using the SELECT (Share Each Length-class's Catch Total) method (Millar, 1992) and a model of between-set variation in a similar way to the model developed by Fryer (1991) for between-haul variation for towed gears and applied to gill nets by Madsen *et al.* (1999). The aim was to identify an adequate mesh size for reducing the amount of juveniles caught without strongly affecting the income of the fishermen. Moreover, adopting a larger mesh size would also reduce the number of accompanying species caught, including *Chelidonichthys lucernus, Squilla mantis, Aporrhais pespelecani* and *Liocarcinus vernalis* which are discarded either because they are small and/or damaged individuals or for their low commercial value (Grati *et al.*, 2004).

MATERIALS AND METHODS

Study area

The study was carried out in the north-central Adriatic Sea inside a rectangular area (24 x 4 km) extending from 2 to 6 km from the coast (Fig. 1), on a sandy-mud seabed and at depths ranging from 9 to 14 m. This fishing area was suggested by the local gill netters for the great abundance of sole.

Experimental fishing trials

The technical parameters of gill nets used for the selectivity experiments were chosen based on a previous study carried out on the local small-scale fisheries (Grati *et al.*, 2002). Five mesh sizes were adopted: three of them are currently used by fishers (nominal mesh opening = 64, 68 and 72 mm), while the other two were experimental measures (66 and 70 mm). For each nominal mesh size, the effective opening was measured on a sample of 50 randomly chosen meshes using a steel ruler connected to a 200 g weight to stretch the mesh. The mean values obtained for each mesh size were used in the calculations.

All the nets were made of 0.20 mm PA monofilament and the line was green in colour.

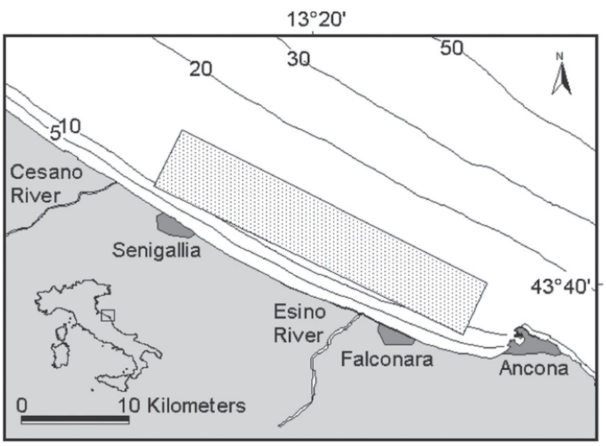

Fig. 1. – Map of the study area in the north-central Adriatic Sea.

TABLE 1. – Technical features of the experimental sole gill nets. HR = Hanging Ratio.

Mesh opening (mm)	Height		Length				
	N. of meshes	meters	N. of meshes	Floatline		Leadline	
				meters	HR	meters	HR
64.2	32	2.06	2000	50.0	0.39	52.0	0.40
65.2	31	2.02	2000	50.7	0.39	52.7	0.40
67.8	30	2.03	2000	52.8	0.39	54.8	0.40
70.2	29	2.04	2000	54.6	0.39	56.6	0.40
71.8	28	2.01	2000	55.9	0.39	57.9	0.40

The net panels of different mesh sizes had the same number of mesh openings (2000) as well as the same hanging ratio on the floatline (0.39) and on the leadline (0.40; Table 1). Consequently, the height and length of the net panels differed slightly among the mesh sizes.

The floatline was a 5-mm PP line with float type B4/40 and a 22 g buoyancy. The floats were hung on the line at 5 m intervals. The leadline consisted of a 50 g/m rope and was about 4% longer than the floatline.

A total of 40 nets (8 for each mesh size) were randomly arranged in one fleet leaving an escaping area of about 1.5 m between adjacent nets to avoid a guiding effect from one net to the next.

A total of 28 sets (Table 2) were carried out in the period spring–early summer 2004 and 2005 using a fibreglass planning fishing vessel (Loa = 10.6 m; GRT = 8.12; engine power = 2x300 HP). The gill nets were fished from dusk to dawn, for a set time of 9-14 hours.

In the same period, fishing trips using rapido trawls were carried out to gather information on the demography of the sole population inhabiting the study area.

The rapido trawl resembles a toothed beam-trawl and is made of an iron frame with 3-5 skids and a toothed bar on its lower side. A nylon net bag is tied to the frame and its lower side is protected by a reinforced rubber diamond-mesh matting. These gears are commonly used to exploit flat fish along the Italian side of the Adriatic Sea and are usually towed at a greater speed (up to 10-13 km h^{-1}) in comparison to the otter trawl nets; this is the reason for their name, "rapido", which is the Italian word for "fast".

Two rapido trawls with a mouth opening of 3.1 m and with 3 skids were used in each haul. The codend of the two gears was made of the same net and the mesh opening was measured by taking samples of 20 randomly chosen meshes in each codend using the ICES Mesh Gauge (strength = 40 N). The mean value was 36.8±0.2 mm. A smaller mesh size was not adopted due to the presence of large amounts of debris in the study area, mainly shells of dead bivalves. Nevertheless, in terms of sole retention, a previous study on rapido trawl selectivity evidenced a L50 of 15.5 cm TL for *S. solea* in the case of a 41.5-mm codend mesh size (Ferretti and Froglia, 1975). Moreover, Pagotto and Piccinetti (1988) reported that the youngest soles occurring in the coastal area in spring and summer should have a mean TL of about 20 cm (age class 1). Based on this information, a rapido trawl with a 36.8-mm mesh codend should catch most of the sole specimens occurring in the study area and hence would represent an efficient sampler in order to draw a good picture of the demographic structure of sole population at sea (blank sample).

TABLE 2. – Fishing trials carried out with the experimental gill nets. The gill net used in each set had a length of 2112 m.

Set N.	Setting date	Fishing time	Depth (m)	N. of soles
1	27/04/2004	13 h 48 min	12	17
2	28/04/2004	13 h 38 min	10	26
3	06/05/2004	11 h 10 min	10	124
4	09/05/2004	12 h 19 min	10	42
5	17/05/2004	10 h 56 min	12	31
6	19/05/2004	13 h 46 min	12	44
7	26/05/2004	12 h 34 min	12	38
8	15/06/2004	10 h 52 min	13	33
9	16/06/2004	12 h 53 min	13	39
10	20/07/2004	11 h 02 min	12	100
11	22/07/2004	9 h 36 min	14	57
12	26/04/2005	12 h 30 min	13	34
13	28/04/2005	14 h 30 min	12	118
14	10/05/2005	12 h 00 min	15	34
15	16/05/2005	11 h 40 min	14	50
16	25/05/2005	13 h 15 min	14	76
17	12/06/2005	14 h 50 min	12	107
18	13/06/2005	12 h 40 min	12	138
19	15/06/2005	14 h 05 min	12	77
20	16/06/2005	13 h 10 min	12	57
21	20/06/2005	14 h 15 min	13	51
22	21/06/2005	14 h 05 min	12	43
23	22/06/2005	12 h 15 min	12	48
24	23/06/2005	11 h 00 min	11	84
25	28/06/2005	14 h 30 min	10	46
26	07/07/2005	13 h 40 min	12	85
27	19/07/2005	14 h 00 min	13	16
28	26/07/2005	11 h 00 min	12	14

TABLE 3. – Fishing trials carried out with rapido trawls in the period spring–early summer 2004 and 2005.

Trial N.	Date	Hauls	Mean haul duration (min±s.d.)	Mean speed (km h^{-1}±s.d.)	Mean depth (m±s.d.)	N. of soles
1	23/04/2004	10	24.3±4.1	8.1±0.3	12.0±0.5	360
2	21/05/2004	11	24.6±5.9	8.2±0.1	11.1±1.1	280
3	25/06/2004	9	29.3±5.3	8.3±0.4	11.7±0.4	436
4	22/07/2004	10	27.1±8.8	8.0±0.0	11.8±0.3	297
5	13/05/2005	10	30.1±8.6	8.3±0.5	13.5±0.8	130
6	20/06/2005	10	38.6±8.4	9.5±0.1	12.7±1.2	114
7	22/07/2005	10	29.9±3.0	9.4±0.4	12.2±0.6	122

A total of 70 hauls was carried out using a wooden fishing trawler (Loa = 17.2 m; GRT = 9.97; engine power = 250 HP). The fishing speed was about 8 km h^{-1} and each haul lasted about 30 minutes to limit the amount of debris in catches. Depth, geographical position and fishing time were recorded in each trip (Table 3).

Analysis of catches

The Total Length of each sole in the catches was measured to the nearest 0.5 cm below and recorded according to mesh size and set for the gill net and according to haul for the rapido trawls.

Catch per Unit Effort (CPUE) was computed for the gill nets as the number of soles caught with 400 m of net and for the rapido trawls as the number of soles caught per square kilometre. The CPUEs obtained with the five mesh sizes were compared using a 1-way ANalysis Of VAriance (ANOVA). Prior to statistical analysis, normal distribution and heterogeneity of variances were evaluated by Kolmogorov-Smirnov and Bartlett tests respectively (Lindman, 1992). When the latter test was significant, the relationship between the means and the respective SD were analysed to check whether the ANOVA assumptions were effective. Data were log-transformed based on these tests.

In addition, in order to evaluate whether the method of capture affected the size selectivity of the soles caught, each specimen retained by gill nets was characterised as follows (Baranov, 1914):

1. mouth clamped (MC) – net twine caught in the mouth;
2. gilled (GI) – fish meshed immediately behind the gill cover (no twine in the mouth);
3. wedged (WE) – fish meshed around the body somewhere behind the gill cover (no twine in the mouth).

The average length of soles caught by the different mesh sizes as well as that of the specimens caught in different ways by the same mesh were statistically compared using the non-parametric Mann-Whitney U-test (Siegel, 1956).

Estimation of gill net selectivity

The size selectivity of a gear can be defined by a curve that gives for each fish size the proportion of the total population of that size which is caught and retained by a unit operation of the gear (Lagler, 1968).

The methods for estimating gill net selectivity are usually classified into two main groups based on whether there is information available on the length distribution of the fish or not:

1. Direct methods - the size structure of the population available to the gill net is known; the population demography may be inferred using various stock assessment techniques such as mark-recapture experiments (e.g. Hamley and Regier, 1973; Borgstrøm, 1989, 1992), acoustic surveys (e.g. Rudstram *et al.*, 1987) or from fishing using non-mesh selective gears (e.g. Borgstrøm, 1989; Winters and Wheeler, 1990);

2. Indirect methods – information on the population demography is not known and the gill net selectivity may be estimated indirectly using nets with different mesh sizes simultaneously. This is possible if fish of a given size are equally available to all mesh sizes and if the selectivity only depends on the fish size and mesh size (Hovgård and Lassen, 2000).

In the present study the size selectivity of sole gill nets was calculated indirectly using the SELECT (Share Each Length-class's Catch Total) method (Millar, 1992) with the GILLNET (Generalised Including Log-Linear N Estimation Technique) software (Constat, 1998a). Data from rapido trawl trials were only used to evaluate the impact of the gill net mesh sizes considered in the sole population occurring at sea in the study period.

Initially developed for trawling (Millar, 1992), the SELECT method was then extended to set nets (Millar and Holst, 1997) and represents a general framework for analysing the selectivity of all types of fishing gears. Parameter estimation is carried out by Maximum Likelihood (ML), which also allows the between-haul/set variability to be taken into account (Millar, 2000).

The SELECT method assumes that the catches (n_{lj}) by length class (l) and gear size (j) follow a Poisson distribution with the following parameters: a) the abundance of a length l fish coming into contact with the combined net (λ_l); b) the relative fish intensity (probability that a fish of length l will come into contact with the gear j given that it has come into contact with combined gear $p_j(l)$); c) the retention probability of a length l fish in gear size j ($r_j(l)$):

$$n_{lj} \approx \text{Pois}\left(p_j(l)\lambda_l r_j(l)\right)$$

The log-likelihood of n_{lj} is:

$$\sum_l \sum_j \left\{ n_{lj} \log_e \left[p_j \lambda_l r_j(l) \right] - p_j \lambda_l r_j(l) \right\}$$

The parameters of five selectivity curves (normal scale, normal location, log normal, gamma and bimodal) generated by GILLNET software and usually employed in studies on set net selectivity (Miller and Holst, 1997; Madsen *et al.*, 1999; Fonseca *et al.*, 2005; Erzini *et al.*, 2006; Sbrana *et al.*, 2007) were estimated in order to identify the curve that best fitted the catch data:

$$\text{Normal scale: } \exp\left(-\frac{\left(L - k_1 \cdot m_j\right)^2}{2k_2 \cdot m_j^2}\right)$$

$$\text{Normal location: } \exp\left(-\frac{\left(L - k \cdot m_j\right)^2}{2\sigma^2}\right)$$

Log-normal:

$$\frac{1}{L}\exp\left(\mu_1 + \log\left(\frac{m_j}{m_1}\right) - \frac{\sigma^2}{2} - \frac{\left(\log(L) - \mu_1 - \log\left(\frac{m_j}{m_1}\right)\right)^2}{2\sigma^2}\right)$$

$$\text{Gamma: } \left(\frac{L}{(\alpha - 1)\cdot k \cdot m_j}\right)^{\alpha - 1} \exp\left(\alpha - 1 - \frac{L}{k \cdot m_j}\right)$$

Bi-normal:

$$\exp\left(-\frac{\left(L - a_1 \cdot m_j\right)^2}{2\left(b_1 \cdot m_j\right)}\right) + \omega \cdot \exp\left(-\frac{\left(L - a_2 \cdot m_j\right)^2}{2\left(b_2 \cdot m_j\right)^2}\right)$$

These models observe the *"principle of geometric similarity"* (Baranov, 1948), with the exception of the "normal location". This principle states that since all meshes are geometrically similar and all fish of the same species (within a reasonable size range) are also geometrically similar, the selectivity curves for different mesh sizes must be similar. Therefore, selectivity s is the same for any combination of mesh size m and fish size l for which the ratio l/m is the same:

$$s(l, m) = s(kl, km),$$

where k is a constant. In this context the ratio l/m is termed Relative Length (RL).

The shape of the selection curve that best fits the catch data was chosen based on two criteria: a) the smallest value for the ratio deviance/degrees-of-freedom; b) a critical p-level of 0.05 for goodness of fit.

The only effort parameter included in the modelling was the floatline length, as it varied between the different mesh sizes and there were no differences in soak times between mesh sizes.

The selectivity parameters of the mean curve were estimated using REsidual Maximum Likelihood (REML) analysis with the EC MODEL (Vers. 1.1) software (Constat, 1998b) in a similar way to the model determined by Fryer (1991) of between-haul variation for towed gears in order to avoid underestimation of variance.

The selectivity parameters from the individual sets can be assumed to vary around a common mean α according to a multivariate normal distribution:

$$\nu_i \approx N(\alpha, D)$$

where α is the parameter vector describing the mean curve which has to be estimated and D is the covariance matrix for the between-set variation.

Provided that enough fish are caught, the Maximum Likelihood (ML) estimate $\bar{\nu}_i$ of the selectivity parameters can be assumed to be multivariate normal:

$$\bar{\nu}_i \approx N(\nu_i, R_i)$$

where R_i is the covariance matrix for random error within the set, hence:

$$\bar{\nu}_i \approx N(\alpha, R_i + D)$$

Estimates of α and D were obtained by maximizing the log-likelihood function.

In practice, this can be accomplished via the expectation-maximisation (EM) algorithm (Dempster *et al.*, 1977). The estimates $\bar{R}_i$ of the within-set covariance matrices, obtained from the initial estimation in relation to the set, were used in place of R_i.

Some sets were excluded from the REML analysis because the corresponding selectivity parameters differed so much from those obtained for all other sets. This was due either to the small sample size (set N. 27 and 28) or to unrealistic size-frequency distributions of catches between meshes characterised by a decreasing average TL with the increase of the mesh size (set N. 6 and 20).

RESULTS

Gill net catches

A total of 398 specimens of *S. solea* were caught with the 64.2 mm mesh, 381 with the 65.2 mm mesh, 328 with the 67.8 mm mesh, 287 with the 70.2 mm mesh, and 235 with the 71.8 mm mesh. Similarly, the Catch per Unit Effort decreased with the increment of the mesh size, ranging from 14.2±1.8 ind. 400 m^{-1} and 1.2±0.1 kg 400 m^{-1} (64.2 mm mesh) to 8.4±0.8 ind. 400 m^{-1} and 0.8±0.1 kg 400 m^{-1} (71.8 mm mesh) (Fig. 2); however, the differences were not statistically significant (number of individuals: p = 0.085; biomass: p = 0.315).

The size-frequency distributions of total catches in relation to mesh size pooling over all sets showed a slight shift to the right for the first cohort and a gradual rise in the second cohort, which was represented by larger specimens with the increase of mesh size (Fig. 3). Due to the low number of large soles in catches, the second cohort was much less evident when considering the single set catches.

The shifting towards larger mesh sizes was also confirmed by the mean TL which significantly increased from 20.88±0.09 cm in the smallest mesh size (64.2 mm) to 21.88±0.15 cm in the largest one

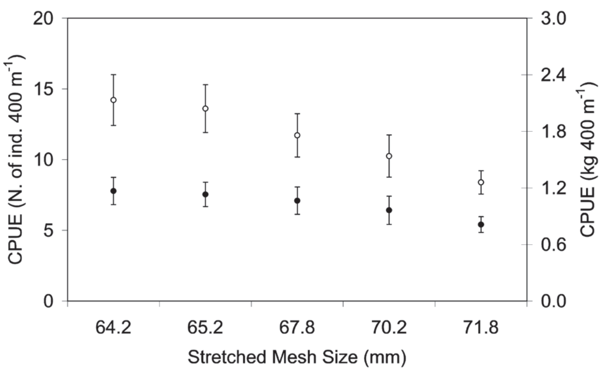

FIG. 2. – Gill net catches: Catch per Unit Effort (± standard error) of *S. solea* in number of individuals (white dots) and weight (black dots) per 400 m of gill net.

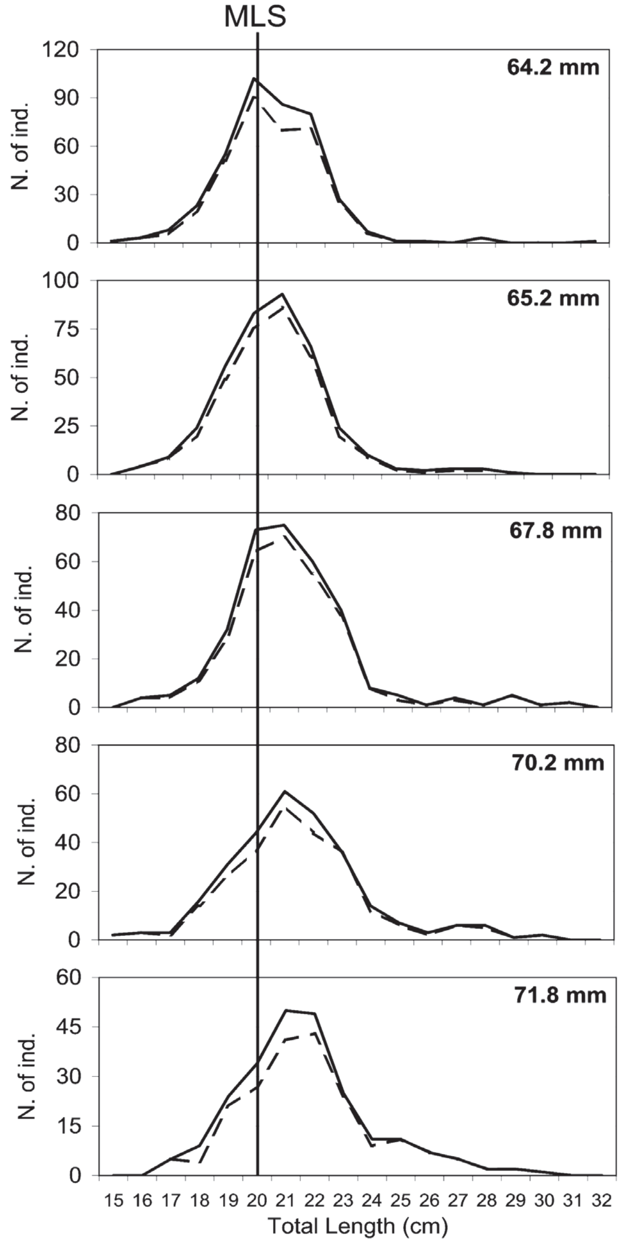

FIG. 3. – Size-frequency distributions of the soles caught with gill nets of different mesh sizes computed with pooled data from all sets and from the sets selected for the REML analysis. MLS = Minimum Landing Size (20 cm TL). Broken lines = all sets; continuous lines = sets used in REML analysis.

TABLE 4. – P-values of Mann-Whitney U-test applied to the Total Lengths of soles caught with the different mesh sizes. ** = highly significant; * = significant.

	64.2 mm	65.2 mm	67.8 mm	70.2 mm
65.2 mm	0.926	-	-	-
67.8 mm	0.000**	0.001**	-	-
70.2 mm	0.000**	0.000**	0.218	-
71.8 mm	0.000**	0.000**	0.021*	0.317

(71.8 mm) (Table 4). At the same time the fraction of specimens under the MLS decreased from 23-24% (64.2 and 65.2 mm meshes) to 16% (71.8 mm mesh) (Fig. 3), which correspond respectively to 16% and 9% of the weight of the total sole catch.

Ninety-eight percent of soles caught had an RL between 2 and 4.

The analysis of the method of capture evidenced that MC was the most important method of retention as it included 74% (65.2 mm mesh) to 83% (70.2 mm mesh) of the total number of soles caught (Fig. 4). GI was the second most important method of capture and accounted for 14% (67.8 mm mesh) to 23% (65.2 mm mesh) of soles in catches, while the WE specimens were very rare (2-3%).

In each mesh size, the Total Length of the individuals retained with the three methods of capture did not show statistical differences (Fig. 5), except for the MC soles which were significantly smaller than the GI soles in the 67.8 mm ($p = 0.002$) and than the WE fish in the 71.8 mm mesh ($p = 0.036$). No sole appeared damaged after being removed from the net, independent of the method of capture.

Rapido trawl catches

A total of 1739 soles were caught during rapido trawl trials and a mean abundance of 873.5±98.1 individuals km^{-2} was observed in the whole sampling period.

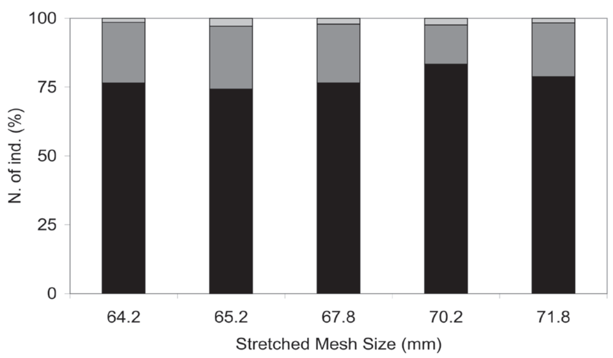

FIG. 4. – Percentage of soles caught with gill nets subdivided according to the method of capture. Black = mouth clapped; dark grey = gilled; light grey = wedged.

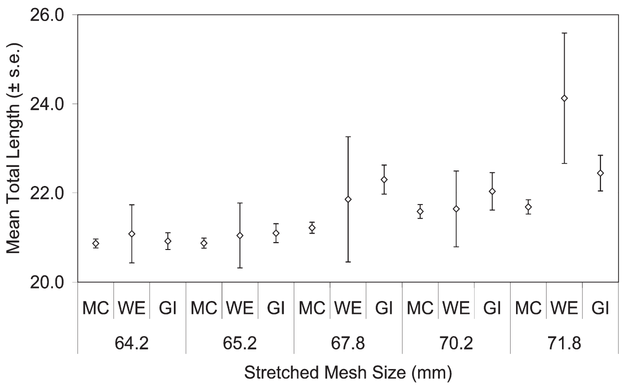

FIG. 5. – Mean Total Length of soles caught in gill nets with the three different methods of capture. MC = mouth clapped; WE = wedged; GI = gilled.

The specimens caught had an average TL of 20.64±0.05 cm and fell into the size range 15 to 31 cm TL (Fig. 6). The size-frequency distribution was clearly bi-modal with a first mode at 20 cm TL and a second one at 26 cm TL. The first cohort was by far the most abundant, accounting for about 96% of the population at sea.

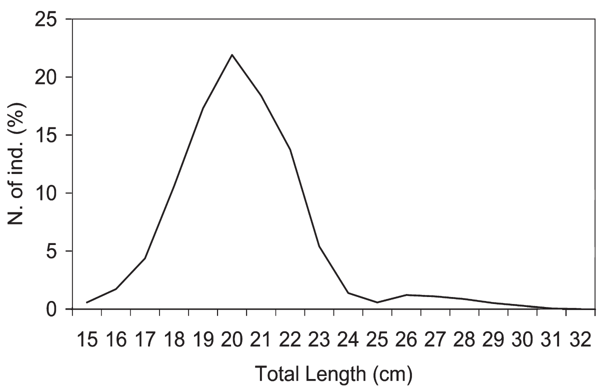

FIG. 6. – Size-frequency distribution of the soles caught with the rapido trawl with a 36.8 mm mesh codend.

Gill net selectivity

Fitting selection curves to single set data

In most cases uni-modal selection curves were found to fit the catch data of each set operation better than the bi-normal one and provided the smallest values for the ratio deviance/degrees-of-freedom and the highest p-level values (Table 5). A selection curve could not be estimated for sets N. 2 and N. 12.

As the uni-modal selection curves gave similar values for the ratio deviance/degrees-of-freedom and similar p-values, the most suitable selection curve

TABLE 5. – Model deviance for individual sets with the corresponding goodness of fit p-value. DF = degrees-of-freedom. Critical level for goodness of fit = 0.05. The significant p-values are shown in italic.

Set N.	Normal scale		Normal location		Log-normal		Gamma		Bi-normal	
	dev/DF	p-value	dev/DF	p-value	dev/DF	p-value	dev/DF	p-value	dev/DF	p-value
1	28.3/25	0.295	28.2/25	0.297	28.2/25	0.300	28.1/25	0.301	25.1/22	0.295
3	41.7/50	0.791	42.2/50	0.776	42.4/50	0.767	42.1/50	0.779	41.2/47	0.712
4	40.1/30	0.102	40.2/30	0.101	40.3/30	0.100	40.2/30	0.100	40.1/27	*0.050*
5	45.8/34	0.084	45.8/34	0.086	45.8/34	0.085	45.8/34	0.085	31.4/31	0.445
6	26.1/22	0.247	26.0/22	0.253	26.1/22	0.248	26.1/22	0.248	26.1/19	0.127
7	20.4/26	0.772	20.5/26	0.768	20.6/26	0.760	20.5/26	0.765	20.4/23	0.617
8	17.7/22	0.725	17.5/22	0.733	17.8/22	0.719	17.7/22	0.721	16.1/19	0.648
9	50.3/26	*0.003*	50.9/26	*0.003*	51.0/26	*0.002*	50.8/26	*0.003*	26.0/23	0.303
10	26.8/30	0.631	27.0/30	0.630	26.7/30	0.638	26.8/30	0.637	26.8/27	0.472
11	31.6/26	0.206	32.0/26	0.192	32.0/26	0.194	31.9/26	0.198	31.6/23	0.108
13	41.6/46	0.655	40.6/46	0.699	40.9/46	0.685	41.0/46	0.681	-	-
14	32.0/26	0.193	32.1/26	0.190	32.0/26	0.191	32.0/26	0.192	-	-
15	42.6/38	0.281	42.4/38	0.287	42.0/38	0.294	42.3/38	0.291	-	-
16	45.9/50	0.640	46.4/50	0.617	47.1/50	0.592	46.7/50	0.608	43.3/47	0.625
17	71.6/46	*0.009*	70.8/46	*0.011*	70.7/46	*0.011*	71.0/46	*0.011*	59.4/43	*0.049*
18	41.4/42	0.495	42.2/42	0.464	42.1/42	0.467	41.8/42	0.480	41.5/39	0.364
19	30.7/30	0.432	31.1/30	0.412	30.9/30	0.422	30.8/30	0.427	30.7/27	0.285
20	33.6/38	0.675	33.7/38	0.668	33.5/38	0.677	33.5/38	0.678	30.4/35	0.690
21	43.7/34	0.124	43.9/34	0.120	43.8/34	0.120	43.8/34	0.121	43.9/34	0.065
22	34.1/38	0.651	34.5/38	0.634	34.8/38	0.618	34.5/38	0.631	50.2/35	*0.047*
23	33.5/30	0.302	33.4/30	0.305	33.6/30	0.298	33.5/30	0.300	-	-
24	42.2/38	0.295	42.0/38	0.304	42.0/38	0.300	42.1/38	0.299	-	-
25	27.5/26	0.385	27.5/26	0.382	27.4/26	0.386	27.5/26	0.386	23.4/23	0.439
26	46.9/34	0.070	46.0/34	0.082	46.0/34	0.084	46.2/34	0.079	-	-
27	19.2/18	0.382	-	-	19.1/18	0.385	19.1/18	0.384	-	-
28	24.6/26	0.543	-	-	24.3/26	0.559	24.4/26	0.552	-	-

was chosen by analysing the selectivity parameter variability of each model and focusing the REML analysis on the model that showed the highest homogeneity between parameters.

The log-normal selection curves showed a low Coefficient of Variation (CV) for both parameters with respect to the other models (Table 6); hence, it was chosen for the subsequent between-set variation analysis.

Between-set variation analysis

A total of 22 sets was included in the REML analysis considering the log-normal selection model. Sets N. 6, 20, 27 and 28 were rejected because the parameters differed too much from the mean values (Table 6). Most set by set selection curves were similar showing similar spread and a mode included in the range 3.1-3.7 RL (Fig. 7). The parameters of the mean log-normal selection curve estimated with the REML analysis are reported in Table 7. The ratio between length of maximum retention and mesh size was 3.30. The TL with 50% retention probability on the left side of the curve ranged from 18.8 cm (64.2 mm mesh) to 21.1 cm (71.8 mm mesh), while on the right side it varied from 23.9 cm in the smallest mesh size to 26.8 cm in the largest one (Table 8). The op-

TABLE 6. – Uni-modal selection curve parameters for individual sets and mean values with the correspondent Coefficient of Variation (CV%). CV<100: low variance; CV>100: high variance.

Set N.	Normal scale		Normal location		Log-normal		Gamma	
	k_1	k_2	k	σ	μ	σ	k	α
1	3.16	0.40	3.13	2.52	3.01	0.11	0.04	73.87
3	3.38	0.48	3.31	3.43	3.08	0.16	0.08	44.31
4	0.31	0.05	0.31	3.69	3.02	0.19	0.01	31.79
5	0.33	0.04	0.33	3.05	3.06	0.14	0.01	55.78
6	6.00	0.91	29.34	56.91	6.05	0.51	1.19	14.37
7	3.21	0.21	3.20	1.46	3.03	0.07	0.01	218.97
8	3.32	0.21	3.32	1.48	3.07	0.07	0.01	227.10
9	0.35	0.04	0.36	3.36	3.18	0.15	0.01	55.57
10	3.70	0.55	3.76	4.38	3.23	0.18	0.11	35.83
11	3.44	0.33	3.42	2.40	3.10	0.11	0.04	96.54
13	0.34	0.03	0.33	2.18	3.06	0.10	0.00	107.34
14	0.40	0.05	0.41	3.98	3.30	0.16	0.01	50.44
15	0.46	0.07	0.46	5.94	3.44	0.21	0.02	28.77
16	3.50	0.46	3.45	3.26	3.12	0.15	0.07	51.84
17	0.33	0.05	0.32	2.99	3.05	0.13	0.01	55.02
18	3.51	0.44	3.47	3.07	3.12	0.13	0.06	61.32
19	3.28	0.29	3.26	2.05	3.05	0.09	0.03	121.33
20	5.69	1.02	7.60	14.43	4.10	0.36	0.53	14.58
21	3.57	0.66	3.60	5.25	3.20	0.23	0.16	24.04
22	3.25	0.22	3.24	1.50	3.04	0.07	0.01	217.68
23	3.47	0.44	3.50	3.35	3.16	0.16	0.08	48.02
24	0.37	0.06	0.37	3.95	3.18	0.16	0.01	41.68
25	3.46	0.37	3.44	2.64	3.12	0.12	0.05	77.74
26	0.35	0.04	0.35	2.65	3.11	0.11	0.00	80.28
27	0.00	2.57	-	-	0.00	1.65	1.72	1.00
28	0.00	1.28	-	-	0.00	0.67	0.45	1.00
Mean	2.47	0.31	2.15	3.12	3.17	0.15	0.18	70.62
CV%	73.0	90.4	71.2	36.7	7.2	43.3	223.6	89.1

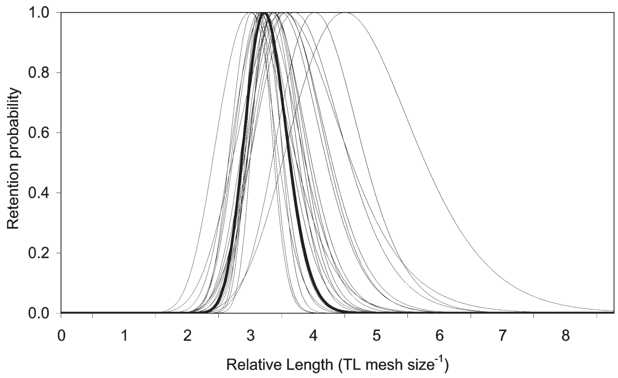

FIG. 7. – Log-normal selection curves for individual sets (thin lines) and estimated mean selection curve given by REML analysis (thick line).

TABLE 7. – Parameter estimates for the mean log-normal selection curve generated by the REML analysis. SD = standard deviation; DF = degrees-of-freedom. Transformed parameters are in cm.

	μ	σ
Estimate	3.066	0.102
SD	0.012	0.008
t-value	245.899	12.626
DF	39	39
exp (estimate)	21.455	1.107

TABLE 8. – Total length (TL; cm) of soles with 50% retention probability on the left side of the log-normal selection curve, 100% and 50% on the right side of the log-normal selection curve.

Stretched mesh size	TL50% left	TL100%	TL50% right
64.2 mm	18.8	21.2	23.9
65.2 mm	19.1	21.6	24.3
67.8 mm	19.9	22.4	25.3
70.2 mm	20.6	23.2	26.2
71.8 mm	21.1	23.8	26.8

timal retention size fell in the interval 21.2 cm (64.2 mm mesh) to 23.8 cm (71.8 mm mesh).

The retention probability for the length class 20 cm (MLS) gradually decreased from 0.84 (64.2 mm mesh) to 0.24 (71.8 mm mesh) (Fig. 8).

DISCUSSION

Along the Italian side of the northern and central Adriatic Sea *S. solea* is targeted both by rapido trawlers and by small-scale fishermen with gill nets. The latter represents the most important activity of the local fishermen from spring to autumn, when sole juveniles of age classes 1 and 2 are abundant in the coastal waters. Nevertheless, the selectivity of sole gill nets has never been investigated in this area until now. The present study is the first effort in this field and aims to provide useful information for resource management.

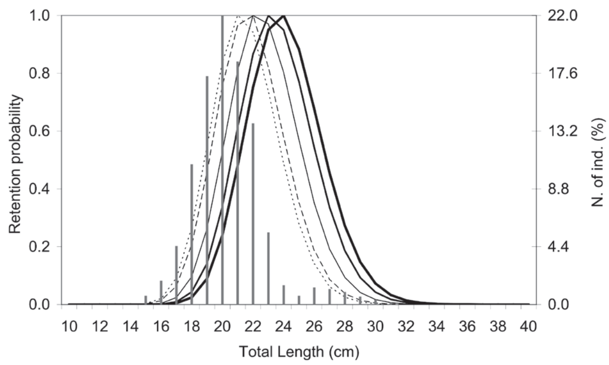

FIG. 8. – Log-normal selection curves for the 5 gill net mesh sizes used in the selectivity experiments and size-frequency distribution (histograms) of the soles caught in the rapido trawl trials. Dots = 64.2 mm; broken line = 65.2 mm; thin line = 67.8 mm; medium line = 70.2 mm; thick line = 71.8 mm.

The pooled size-frequency distributions of the catches obtained by means of the five gill net mesh sizes tested in the present study were bimodal; the second mode became more and more evident with the increasing mesh size. The distributions were well matched with the demographic structure of the population at sea obtained by rapido trawls. A few authors have suggested that the bimodal shape of catch size distributions of set nets can be due to the combination of more than one capture mechanism (gilling, wedging, entangling; Fonseca *et al.*, 2005; Erzini *et al.*, 2006). Indeed, in our study most of the soles were entangled, specifically mouth clapped, but sometimes it was impossible to establish whether it was the primary capture process or not. In accordance with what Madsen *et al.* (1999) observed, this did not appear to affect the size selection of soles as their mean total length was generally similar for the different methods of capture, i.e. mouth clapping, wedging and gilling. The high variability in the total length of the wedged soles compared to the other two methods of capture was probably due either to the oval body shape of this species or to the fact that *S. solea* when swimming into the net tends to roll itself up. The morphological characteristics of soles (resistance against abrasion, capacity to roll itself up) are probably the main reasons why the quality of fish was not affected by the method of capture. Indeed, soles caught by gill nets are usually considered of higher quality, and hence of higher economic value, than those caught with rapido trawls.

Although the demography of the pooled catches obtained with the different mesh sizes as well as the demography of the population at sea showed two modes, the uni-modal curves gave lower deviance and higher p-values for single set data with respect to the bi-modal curves. In addition, the latter could not be calculated in 28% of the cases. The log-normal showed the highest homogeneity among selectivity parameters and hence it was used in the subsequent REML analysis.

The better fitting of uni-modal curves to single sets was probably a consequence of the scarce occurrence of large specimens in the single catches due to their low abundance in the population at sea, as demonstrated by the demography of the soles caught by rapido trawls. However, the presence of these individuals in the single sets led to a slight skewing on the right side of the estimated log-normal curves.

In a study conducted in the North Sea using the between-set analysis, Madsen *et al*. (1999) found that the bi-modal curve was the best model for describing the selectivity of sole gill nets. In spite of this, the selection range and the length at maximum retention estimated by these authors were close to the values of the log-normal curve obtained in the present study. Our values also agreed with those computed by Sacchi *et al.* (1987) in the English Channel applying the Kitahara method (Kitahara, 1971), and by Francesconi *et al.* (2005) in the eastern Ligurian Sea using the Sechin method (Sechin, 1969) as modified by Reis and Pawson (1992).

From the management point of view, the increment in the mesh size did not negatively affect the catch yields while the percentage of individuals under the MLS in catches noticeably decreased from 16% down to 9% in terms of biomass in the largest mesh size. The estimated log-normal selectivity curves indicated that the retention probability for the 20 cm TL class decreased from 84% in the smallest mesh to 24% in the largest one. This reduction has a relevant ecological importance in spring–early summer when this size class is the most abundant in the population at sea. However, the portion of individuals longer than the MLS proportionally increased in the catches. For example, the retention probability for the 25 cm TL class (size at first sexual maturity; Fisher *et al*., 1987) rose from 28% in the 64.2 mm mesh up to 89% in the 71.8 mm one, which evidences the greater efficiency of the latter mesh size towards adult individuals, whose contribution to the catch biomass shifted from 4% (64.2 mm mesh) to 21% (71.8 mm mesh).

Taking into account that the small specimens have a lower economic value with respect to the large ones, it can be concluded that generally adopting the 72 mm mesh size would represent a good compromise between the conservation of the resource at sea and the economic profit of the local small-scale fishermen.

Indeed, Francesconi *et al*. (2005) indicated an 84.0 mm mesh as the best size for protecting sole juveniles with the maximum economic value of the catch; however, this is probably a consequence of the different spatial distribution of the species in the Ligurian and Adriatic Seas due to the different geomorphological features of these two areas. In fact, the former is characterised by a very narrow continental shelf where the overall sole population tends to concentrate. This favours the catch of adult specimens by small-scale set netters commonly operating in inshore areas. Differently, most of the bottom surface of the northern and central Adriatic Sea consists of continental shelf. Consequently, the sole population spreads out in a very wide area, and has a spatial distribution strictly related to depth: the young specimens tend to concentrate in shallower waters and move offshore up to 50-60 m depth as they grow (GFCM, 2006). Therefore, as gill nets fish in inshore areas, their catches only include a small fraction of large individuals.

However, further investigations along the Italian Adriatic coast with larger mesh sizes are necessary in order to identify the mesh that allows catching undersized specimens to be totally avoided and to evaluate the effects of adopting this mesh size on the economic sustainability of the sole fishery with gill nets.

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